Sequential coupled simulation of a dual source heat pump and shallow geothermal reservoir

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ABSTRACT

The numerical simulation is an important tool for the assessment of exploiting geothermal energy. It can be used in shallow geothermal applications to evaluate the different production scenarios and the sustainability of the system (geothermal reservoir and heat pump) on long term. Moreover, in shallow geothermal projects, to simulate the real behaviour of the system, the load profiles of the end user and variations of the working mode of the heat pump should be taken into account. The present work introduces and describes a coupled numerical model, in which a dedicated Matlab® script has been realized to allow a sequential coupled simulation of a shallow geothermal reservoir exploited with a dual source heat pump. A mathematical model of a dual source heat pump that can work with the ground or the air as source/sink has been developed in Matlab® environment. Each component of the heat pump has been modelled considering the equations that govern the physical phenomena. The dynamic numerical simulator FEFLOW® has been used to simulate the behaviour of the geothermal reservoir, subjected to heat extraction/reinjection by a closed loop vertical heat exchangers field. This methodological approach is useful to evaluate the performance of the coupled system on the long term, and it is important for understanding the advantages and limits of the dual source heat pump in assuring the sustainability over time when heat is exchanged with the ground, avoiding the depletion of geothermal resources. The mathematical models have been validated with experimental data from a geothermal plant located in Tribano (Padova, IT). This is one of the four pilot sites realized within the framework of the H2020 GEOTeCH Project. It consists of eight coaxial borehole heat exchangers 30 m deep, connected to the 16 kW dual source heat pump prototype realized by HIREF S.p.A. The geothermal heat pump system has been working, and monitored, since October 2017 and it provides heating and air conditioning to an office area. Experimental results have been used to verify the new coupled model, and although the preliminary results are encouraging, further study and work are necessary to make it robust and stable for future routine work.

.1. SIMULATION AND MODELLING OF GROUND SOURCE HEAT PUMP SYSTEMS (INTRODUCTION)

A ground source heat pump (GSHP) is a heating/cooling system, consisting of a heat pump, geothermal probes and thermal reservoir. The work of the different parts follow a sequential logic: the heat pump, depending on the building loads, request an energy amount from the geothermal probes, which exchange heat with the thermal reservoir, the ground. (Kavanaugh and Rafferty, 1997). This process causes both short and long-term thermal depletion of the reservoir, which must be predicted and managed by means of numerical simulation, to allow the optimal operation of the GSHP system (Focaccia et al., 2016). Numerical simulation is a standard approach in GSHP projects. The ultimate purpose is to obtain information to improve and optimize the behaviour over time of the system to increase its efficiency and consequently obtain energy savings (Cui et al., 2017). Many software packages exist to numerically simulate the behaviour of the ground subjected to heat extraction/injection cycles. Some notable cases studies of this approach can be found in Al-Khoury et al., 2010, Javed and Claesson, 2011, Pasquier and Marcotte, 2012, Ruiz-Calvo et al., 2015. A limit of the abovementioned applications is that, generally, only the ground part of the system is modelled, after definition of the energy load requested by the heat pump. On the other side, there are various models for the heat pump (Pavkovic and Vilicic, 2001, Jin and Spitler, 2003, Zakula et al., 2011) but few attempt to develop a comprehensive model capable of simulate the behaviour of the heat pump and thermal reservoir. In some recent studies, the performance of GSHPs is evaluated considering the variation of the performance coefficient by implementing simple correlations provided by the manufacturers or by manufacturers' data (Hein et al., 2016, Li et al., 2017). In other cases, the correlations are obtained by experimental measurements conducted on the case study heat pump (Corberán et al., 2018).

This paper presents an attempt of coupling the model of an innovative dual source heat pump (DSHP), able to switch the energy source from ground to air, and the model of a shallow geothermal reservoir, realized with the software package FEFLOW®. The type of coupling between the two simulators is "sequential", which means that the connection between the two simulators takes place through data files generated by the simulators themselves and specially managed by the control program. That is, each simulator generates an output data file that is used as input file for the other simulator in a continuous cycle supervised by an external software layer that controls the correct execution of the coupled simulation also determining its beginning and end.

The potential of the coupled simulator developed has been proved over two working days of an existing case study of a DSHP with 8 geothermal probes installed in Tribano (Padova, Italy) in the framework of the H2020 GEOTeCH Project.

2. HEAT PUMP-GEOTHERMAL SHALLOW SEQUENTIALLY COUPLED SIMULATOR

2.1 Dual source heat pump prototype

The present prototype is a 16 kW invertible heat pump working with R32 as refrigerant. The heat pump is dual source, thus it can work with air or ground as thermal source/sink to absorb or reject heat through a water-to-refrigerant or an air-to-refrigerant heat exchanger. The system can work in nine different operative conditions to provide heating, cooling and domestic hot water. The heat pump is equipped with four heat exchangers working as condenser or evaporator depending on the conditions: three brazed plate heat exchangers (BPHEs, for the user, the domestic hot water production and the ground loop) and a finned coil as air-to-refrigerant heat exchanger. A scroll compressor is mounted on the heat pump with an inverter that allows varying the compressor frequency in order to follow the building thermal load. The refrigerant adopted is R32, a low-GWP refrigerant classified as mildly flammable by ASHRAE Standard 34 (2013). The use of low-GWP refrigerants in the HVAC and refrigeration systems is the actual trend because of the progressively ban of refrigerants with high-GWP (Regulation No 517/2014 of the European Union).

In the present study, the operative conditions when working with ground source both in summer and in winter are considered and the numerical model of the machine operating only with BPHEs is presented. Further data on the heat pump prototype can be found in Zanetti et al., 2018.

2.2 Heat pump numerical model

The numerical model of the heat pump has been developed in Matlab® environment and it considers all the components of the heat pump. In particular, the heat exchangers, which are the most difficult components to simulate, have been discretized in order to apply correlations to calculate the pressure drop and the heat transfer coefficient. This approach allows the model to be more flexible and to estimate the performance of heat pumps operating with various heat exchanger geometries, refrigerants or configurations (summer/ winter mode). A schematic flow chart of the iterative algorithm of the model is displayed in Figure 1. The input parameters for the program are: the geometry of the user and ground heat exchangers, the compressor specifications and the simulation conditions. In particular the required variables are: the compressor frequency [Hz]; the temperature [°C] and mass flow rate [$l \cdot h^{-1}$] of water from the user and from the ground; the refrigerant subcooling at the condenser outlet [K]; the refrigerant superheating at the evaporator outlet [K]; first attempt values for the condensation and evaporation temperatures [°C]. With these inputs, a first attempt value for the compressor efficiency and refrigerant mass flow rate is calculated. After determining all the guess values, an iteration cycle begins: specific programs for the evaporator, the condenser and the compressor are called and at each iteration, new guess values for condensation/ evaporation temperature, compressor efficiency and refrigerant mass flow rate are provided. Every time each of these variables are updated, an intermediate function named "*cycle*" is recalled in order to calculate the properties of the refrigerant in the main points of the thermodynamic cycle.

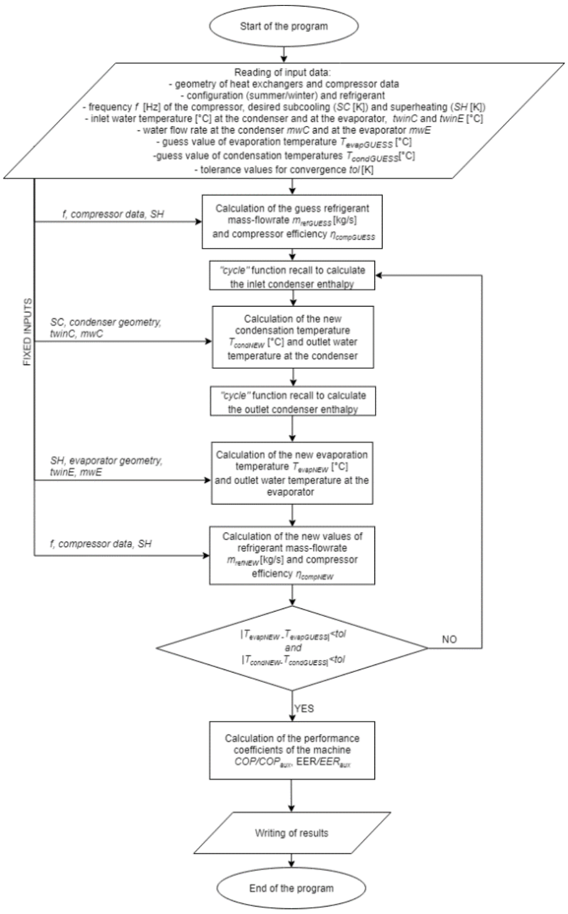

Figure 1. Flow chart of the calculation procedure implemented in the DSHP model.

The iterative procedure ends when the error on the condensation and evaporation temperatures are below a tolerance value (0.005 K).

The new value for the condensation temperature is obtained solving the condenser model. In the model, the condenser of the heat pump is divided into four sections: desuperheating, condensation of superheated vapor, condensation of saturated vapor, subcooling. The calculation procedure starts with a first attempt value for the condensation temperature. For each of the aforementioned zones, a guess value of the related heat exchanger length is initially supposed (the condensation zones are further discretized in smaller elements to improve accuracy). Then calculations are performed in each element to evaluate pressure drop, heat transfer coefficient, logarithmic mean temperature and finally determine the new length for each section as:

$$L_{i,NEW} = \frac{Q_i}{s \cdot HTC_i \cdot \Delta T_{ml,i}} \qquad [1]$$

Where:

- Q_i [W] is the heat exchanged at the $i\text{-}th$ discretization calculated knowing the inlet/outlet refrigerant conditions (mass flow rate, condensation temperature, discharge temperature, subcooling);
- s [m] is the plate width;
- HTC_i [kJ·kg^{-1}·K^{-1}] is the heat transfer coefficient calculated at the $i\text{-}th$ discretization with an available correlation;
- $\Delta T_{ml,i}$ [°C] is the logarithmic mean temperature difference calculated at the $i\text{-}th$ discretization.

When calculations for each section are closed, the sum of the lengths of all regions is compared with the effective length of the condenser:

$$f_{cond} = \frac{\sum_i L_{i,NEW}}{L_{condenser}} \qquad [2]$$

The condensation temperature is then updated until f_{cond} reaches a value close enough to unity.

In the condenser, the heat transfer coefficient for the single phase fluids (water and refrigerant in the region of desuperheating and subcooling) has been calculated with Martin (1996) correlation for single phase and the saturated condensation heat transfer coefficient has been evaluated following the equation proposed by Longo et al. (2015). About the condensation of superheated vapor, the correlation of Webb (1988) has been applied to combine the sensible heat flow rate due to the superheated vapor core (at temperature T_{bulk}) and the latent heat flow rate due to the condensation at the wall:

$$HTC_{sup} = F \cdot HTC_{sp} + HTC_{sat} \qquad [3]$$

where

$$F = \frac{T_{bulk} - T_{sat}}{T_{sat} - T_{wall}} \qquad [4]$$

With HTC_{sp} calculated with equations for single-phase and HTC_{sat} with correlations for convective condensation of saturated vapor.

The same algorithm implemented for the condenser model has been used for the evaporator. In this case, the heat exchanger is subdivided into three sections: the evaporation, dry-out and superheating zones (each zone is then discretized in smaller elements). The iterative procedure starts with a first attempt value of the evaporation temperature, then, calculations are performed for each discretization in order to update the length values (Equation [1]) as for the condenser case.

In the evaporator, the heat transfer coefficient for the single-phase fluids (water and refrigerant in the region of superheated vapor) has been calculated with the Martin (1996) correlation and the heat transfer coefficient during vaporization has been evaluated following the model proposed by Amalfi et al. (2016). Regarding the dryout zone, a linear interpolation has been applied from the heat transfer coefficient in saturated conditions at dryout quality (fixed at 0.95) and that calculated for the single phase condition.

For the calculation of the frictional pressure drop on the water side and for the refrigerant single-phase flow, it has been used Martin (1996) correlation while the Amalfi et al. (2016) correlation is used for the two-phase flow zones in the condenser and in the evaporator models.

Regarding the compressor model, it gives as outputs the global compressor efficiency, the refrigerant mass flow rate and the electric power absorbed; the calculations are the results of the implementation of the compressor maps provided by the manufacturers corrected when necessary for the employed refrigerant.

Eventually, the program calculates the performance coefficients of the heat pump by knowing the heat exchanged at condenser/evaporator and the electrical power consumptions: the model provides a COP/EER value considering only the electrical power absorbed from the compressor, and another value (COP_{aux}/EER_{aux}) considering the overall consumptions of the system (electronics, circulation pumps, etc.).

2.2 Geothermal shallow reservoir numerical model

In order to evaluate the behaviour of geothermal probes exchanging heat with the ground, a dynamic simulator is necessary. In this specific application, the software FEFLOW® (Finite Element Flow simulator) has been chosen, which has a dedicated section for modelling and simulating Borehole Heat Exchangers (BHE) and allows definition of the hydrogeological modelling of the study area. The numerical model implemented is based on the Al-Khoury model (Al-Khoury et al,. 2005 and Al-Khoury and Bonnier, 2006), with generalized formulations for borehole heat exchangers. FEFLOW® allows to realize as many layers as needed, and upload punctual database information for each layer (thermal conductivity, thermal capacity, hydraulic conductivity, temperature). This is important in this application, since vertical temperature gradient around the BHEs varies in time, subjected to both weather conditions and heat exchanged with the DSHP system. Comparison with experimental results has shown the model to be quite robust in predicting heat exchange rates for a GSHP system (Nam et al., 2008), simulating the aquifer thermal plumes and their effect on the BHE closed loop applications (Rivera et al., 2015). Finally, it has been used as a benchmark for evaluating performances of other modelling tools (Nam and Ooka, 2010).

.2.3 Coupled simulator: Matlab script allowing sequential coupled simulation

The Matlab script, named DSHP-BHE controller, has been developed to drive together the numerical simulation of the DSHP and the numerical simulation of the thermal reservoir, run by FEFLOW®. The DSHP-BHE controller can handle FEFLOW® numerical models with BHEs.

The simulation period is subdivided into fixed time steps: for each time step, the user data (the frequency of the compressor and the conditions of the return water from the building) are read and employed as input for the DSHP model. The calculated value of water temperature and flowrate at the ground BPHE outlet are then set as input of the BHE model by the coupled simulator. The output of the FEFLOW® simulation is then read and the temperature of the BHEs are used as new input data for the DSHP numerical simulation. The procedure repeats until convergence for all the defined time steps and, at the end of the simulation period, the coupled simulator reports the results in .csv format.

The conceptual model of the coupled simulation is presented in Figure 2, while Figure 3 shows the flow chart of the DSHP-BHE controller.

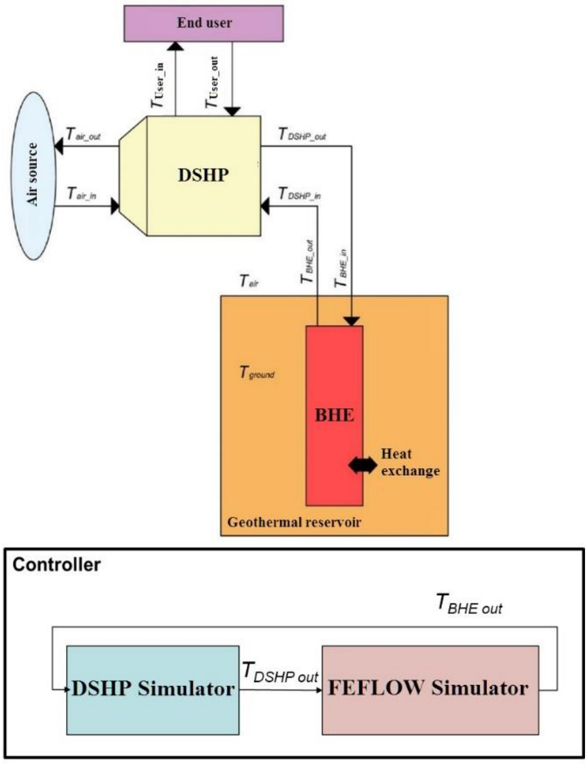

Figure 2. Conceptual model of the coupled simulation.

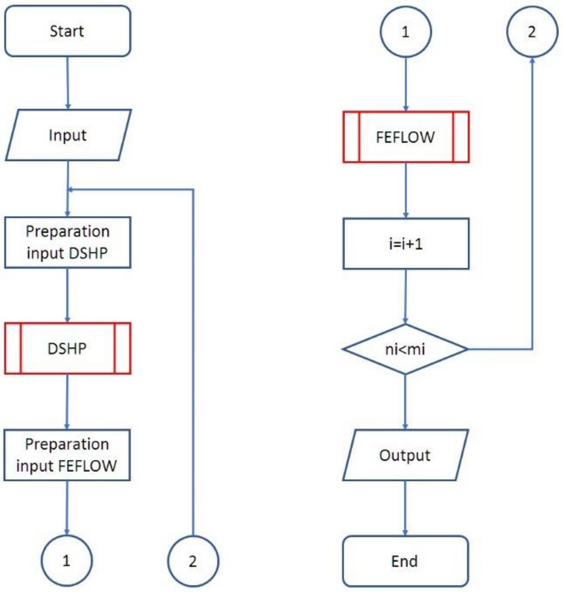

Figure 3. Flow chart of the DSHP-BHE controller allowing the coupled simulation.

3. VERIFICATION AND VALIDATION OF THE SEQUENTIAL COUPLED SIMULATOR WITH DATA FROM THE TRIBANO GEOTECH DEMO SITE

The Tribano demo site is located in the alluvial Po Plain, adjacent to the HIREF S.p.A., which is the manufacturer of the DSHP. 8 Coaxial Borehole Heat Exchangers (CBHE) have been installed, spaced 6 m, down to 30 m deep, without the insertion of grouting, the latter allowed by specific hydrogeological conditions of the area. The eighth CBHE are connected in parallel to a central collector, and subsequently to the DSHP. The system provides heating, cooling and domestic hot water to an office area of HIREF factory. The DSHP started working in November 2017 and, after a testing period, it became fully operational in summer 2018. All further details about the system and its specificities can be found in Tinti et al., 2018.

Beside the eight CBHE, three Observation Boreholes (OB) have been installed to monitor ground temperature. OB1 has been located in the middle between CBHE6 and CBHE8, OB2 1 m distant from CBHE8 and OB3 out of the CBHE field. Monitored values of inlet/outlet fluid temperature circulating inside CBHE8 and in the central collector are also available. All details of the monitoring system can be found in Tinti et al., 2018 as well.

All main parameters and variables of DSHP are also monitored. For the geothermal reservoir side, the monitored parameters are the inlet/outlet fluid temperature from the DSHP and the total flow rate.

The available data have been used to create a model of the geothermal reservoir in FEFLOW®

The model domain implemented extends beyond the CBHE field, for a total surface area of 50 x 78 m^2 and a depth of 44 m. A tetrahedral mesh was used with refinement regions around the eight CBHEs. A set of observations points have been inserted in correspondence of the three OBs. A series of 9 layers was used to detail the geology of the area. Layer 1 is a buffer layer on the top, Layers 2-8 cover the length of the CBHE, 30 m, while Layer 9 guarantees the existence of a geothermal heat flow from the bottom. A difference on the hydraulic head from 1.5 m (top right corner) to 1.6 m (bottom left corner) takes into account groundwater flow movement, according to the available hydrogeological information. Estimated values of ground properties, such as the hydraulic conductivity (1 m/d), the effective porosity (30%), the thermal conductivity (3 $W/(m{\cdot}K)$) and the heat capacity (2.5 $MJ/(m^3{\cdot}K)$) have been used in the model according to the information acquired from hydrogeological studies (Tinti et al., 2018).

Ground natural state is provided by inserting in the nodes at proper distance from the CBHE field the temperature values of the measurements from the three OBs. For any day of the year, OB3 allows to set the condition of undisturbed ground temperature in different periods, while the others permit to determine the starting thermal state around the CBHEs (OB1) and inside the CBHE field (OB2). Temperature values at the nodes among the measured values and the CBHEs are calculated by linear interpolation for each depth.

The model of the CBHE has been realized respecting the geometrical and physical characteristics of the installed prototype. Its main parameters are presented in Table 1 below

Table 1: Dataset of the model of CBHE in FEFLOW®.

Borehole diameter (m)	0.15
Inlet Pipe Diameter (m)	0.09
Inlet Pipe Wall Thickness (m)	0.0029
Outlet Pipe Diameter (m)	0.06
Outlet Pipe Wall Thickness (m)	0.0029
Computational Method	Fully Transient
Heat-transfer coefficients	Computed
Fluid	Pure Water

The hydraulic distribution system of CBHE field is not balanced since the length of the pipes between the collector and each BHE is different. Therefore, different mass flow rates interest different CBHE. The total mass flow rate mass be divided as follows in Table 2.

Table 2: Fraction of Mass Flow Rates in the eight CBHEs.

Number	**Fraction (-)**
CBHE1	0.142
CBHE2	0.193
CBHE3	0.116
CBHE4	0.142
CBHE5	0.101
CBHE6	0.116
CBHE7	0.090
CBHE8	0.101
TOTAL	*1.000*

3.1 Simulation of a day of cooling and comparison with measured values

The first of August 2018 has been chosen as the day of cooling to validate the correctness of the coupled simulation. Monitored ground temperature in the three OBs for 31th of July has been assigned to the nodes of the grid, where available. The temperature in the remnant nodes has been calculated by linear interpolation. Subsequently, these values of ground natural state have been calibrated by performing a simulation in FEFLOW® for the 1st of August, using the inlet temperature values measured in the circuit of CBHE8, and comparing the simulation results with the measured outlet temperature.

Figure 4 shows a horizontal section in FEFLOW® representing the natural state at 2 m depth, while Figure 5 shows the comparison between the outlet temperature results of numerical simulation and the measured temperature values in CBHE8

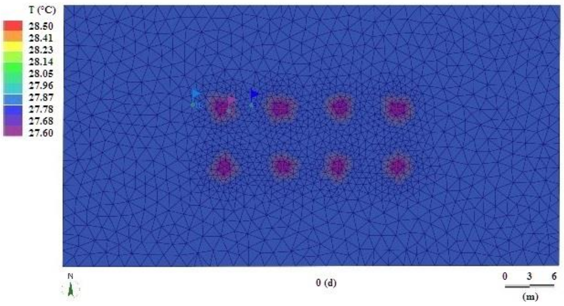

Figure 4: Horizontal numerical model section representing the natural state at 2 m depth for the first of August.

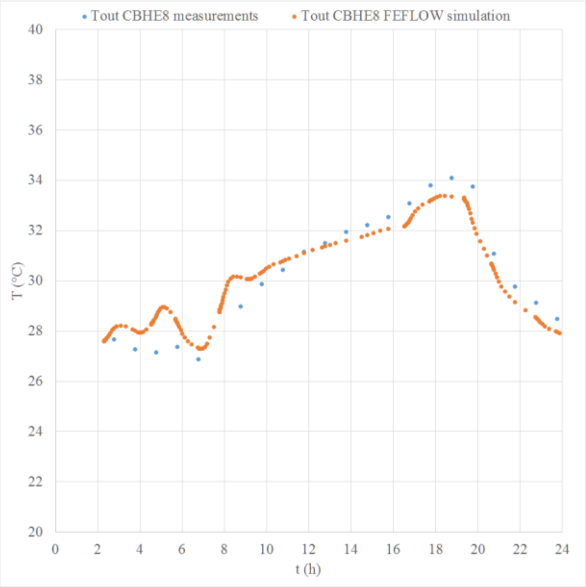

Figure 5: Comparison among temperature measured and simulated values in the outlet circuit of CBHE8, for the first of August.

At first of August, DSHP worked from 10.00 to 20.00. Therefore, only this period has been object of the coupled sequential simulation.

The coupled simulation results and the comparison with measured values are presented in Figure 6 (comparison of fluid temperature from the DSHP to the CBHE field) and Figure 7 (comparison of fluid temperature from the CBHE field to the DSHP).

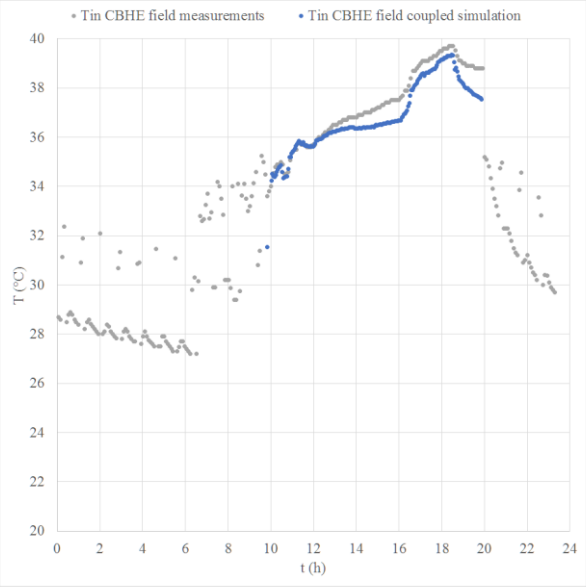

Figure 6: Comparison between measured and simulated values (period: 10.00 - 20.00, summer) of the fluid temperature from the DSHP to the CBHE field, using the sequential coupled simulation.

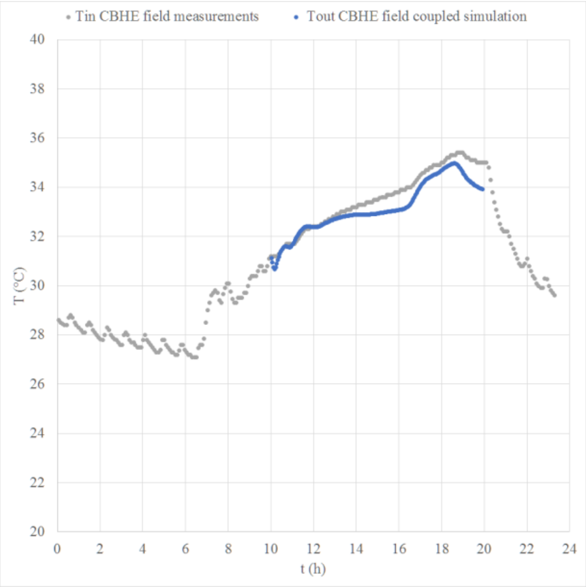

Figure 7: Comparison between measured and simulated values (period: 10.00 - 20.00, summer) of the fluid temperature from the CBHE field to the DSHP, using the sequential coupled simulation.

3.2 Simulation of a day of heating and comparison with measured values

The 28th of January 2019 has been chosen as the day of heating season to validate the coupled simulation. Monitored ground temperature in the three OBs for 27th of January has been assigned to the nodes of the grid, where available. The temperature in the remnant nodes has been calculated by linear interpolation. Subsequently, these values of ground natural state have been calibrated by performing a simulation in FEFLOW® for the 28th of January, using the inlet temperature values measured in the circuit of CBHE8, and comparing the simulation results with the measured outlet temperature.

Figure 8 shows a horizontal section in FEFLOW® representing the natural state at 8 m depth, while Figure 9 shows the comparison between the outlet temperature results of numerical simulation.

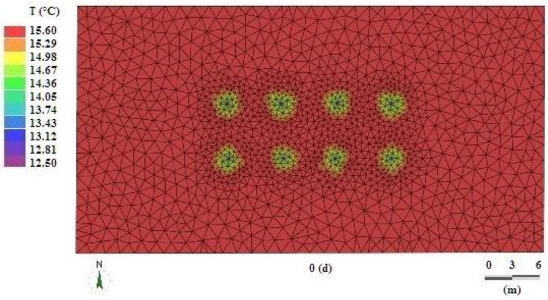

Figure 8: Horizontal numerical model section representing the natural state at 8 m depth for the 28th of January.

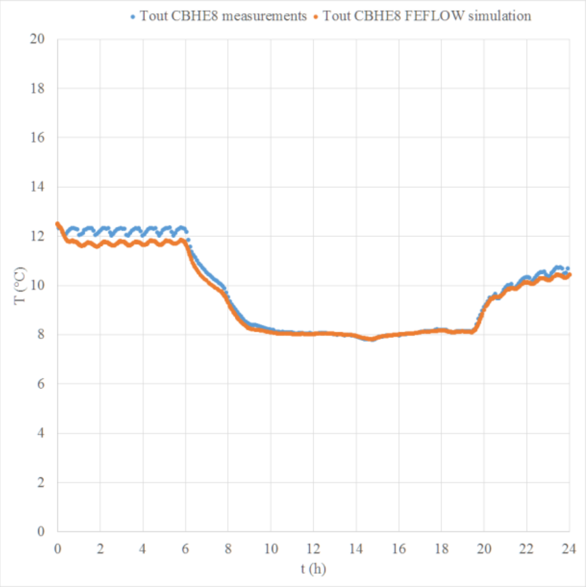

Figure 9: Comparison among temperature measured and simulated values in the outlet circuit of BHE8, for the 28th of January.

At 28th of January, DSHP worked from 8.00 to 18.00. Therefore, only this period has been object of the coupled sequential simulation.

The coupled simulation results and the comparison with measured values are presented in Figure 10 (comparison of outlet temperature from DSHP) and Figure 11 (comparison of outlet temperature from the CBHE field)

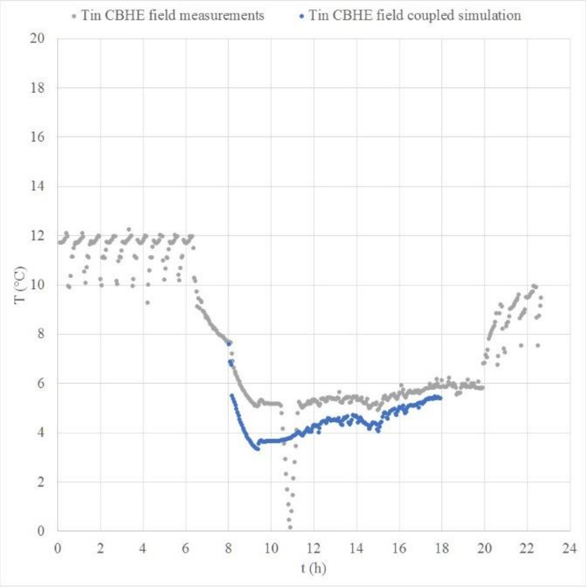

Figure 10: Comparison between measured and simulated values (period: 08.00 - 18.00, winter) of the fluid temperature from the DSHP to the CBHE field, using the sequential coupled simulation.

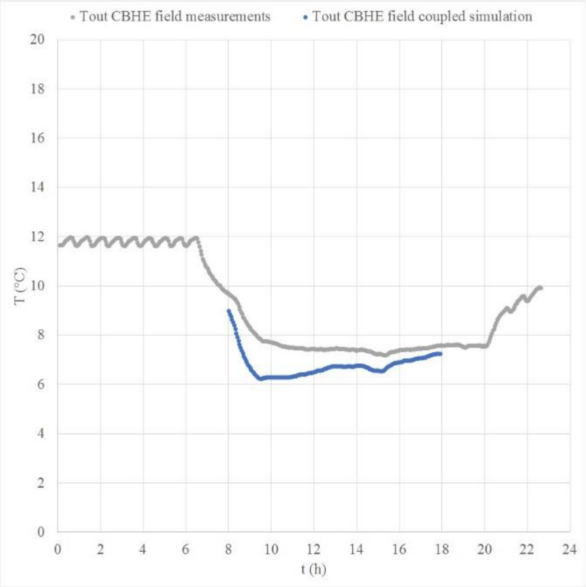

Figure 11: Comparison between measured and simulated values (period: 08.00 - 18.00, winter) of the fluid temperature from the CBHE field to the DSHP, using the sequential coupled simulation.

4. CONCLUSIONS

The present paper describes a first attempt of sequential coupled simulation integrating the dynamic behaviour of the heat pump and the borehole heat exchangers. In the specific case, the effectiveness of the Controller, a MATLAB® script, has been validated over a real case of dual source heat pump linked to a field of eight coaxial borehole heat exchangers. The Controller has worked as expected, and its result is a forecast of inlet/outlet temperature behaviour quite observant of the measured data, on both the DSHP and CBHE sides.

On the other hand, mismatches between simulated and measured values still persist and the resulting gaps are higher than those observed in stand-alone simulations, ground or heat pump side. A preliminary explanation resides in the fact that, in the coupled simulation, any mismatch between the expected and measured value, in both the DSHP and CBHE sides, is amplified by the sequential operation, causing on the medium term a drift, enlarging the gap.

Further studies are foreseen to better manage the sequential coupled simulation and to improve its predictiveness in view of yearly performance analysis.

REFERENCES

Al-Khoury R, Bonnier PG and Brinkgreve R.B.J. Efficient finite element formulation for geothermal heating systems. Part I: steady state. International Journal for Numerical Methods Engineering 63 (2005).

Al-Khoury R, Bonnier PG. Efficient finite element formulation for geothermal heating systems. Part II: transient. International Journal for Numerical Methods Engineering 67 (2006).

Al-Khoury R, Kolbel T, Schramedei R. Efficient numerical modelling of borehole heat exchangers. Computers & Geosciences 36 (2010):1301–15.

Amalfi, R.L, Vakili-Farahani, F., Thome, J.R.: Flow boiling and frictional pressure gradients in plate heat exchangers. Part 2: Comparison of literature methods to database and new prediction methods, *Int. J. Refrig*. 61, (2016), 185-203.

Corberan, J., Cazorla-Marín, A., Marchante Avellaneda, J., Montagud, C.: Dual source heat pump, a high efficiency and cost-effective alternative for heating, cooling and DHW production. *International Journal of Low-Carbon Technologies* (2018), 13 161-176.

Cui, Y., Zhu, J., Twaha, S., Riffat, S. A comprehensive review on 2D and 3D models of vertical ground heat exchangers. Renewable Sustainable Energy Review 94 (2017) 84–114.

Focaccia S., Tinti F., Monti F., Amidei S. and Bruno R., Shallow geothermal energy for industrial applications: a case study, Sustain. Energy Technol. Assessments 16 (2016) 93-105.

Hein, P. Kolditz, O., Görke, U., Bucher, A., Shao, H.: A numerical study on the sustainability and efficiency of borehole heat exchanger coupled ground source heat pump systems, *Applied Thermal Engineering,* (2016), 421-433.

Javed S and Claesson J. New analytical and numerical solutions for the short-term analysis of vertical ground heat exchangers. ASHRAE Transactions 117(1)(2011): 3–12.

Jin, H., Spitler, J.: Parameter estimation based model of water-to-water heat pumps with scroll compressors and water/glycol solutions. *Building Services Engineering Research & Technology*, (2003), 203-219.

Kavanaugh, S. P. and Rafferty, K., “Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings,” American Society of Heating, Refrigerating and Air-Conditioning Engineers, Chiba, 1997.

Li, C., Jinfeng, M., Hua, Z., Zheli, X., Yong, L., Jin, Z.: Numerical simulation of horizontal spiral-coil ground source heat pump system: Sensitivity analysis and operation characteristics, *Applied Thermal Engineering* 110, (2017), 424-435.

Longo, G.A., Righetti, G., Zilio, C., A new computational procedure for refrigerant condensation inside herringbone-type Brazed Plate Heat Exchangers, *International Journal of Heat and Mass Transfer* 82 (2015), 530-536.

Martin, H., A theoretical approach to predict the performance of chevron-type plate heat exchangers, *Chemical Engineering and Processing* 35, (1996), 301-310

Nam Y, Ooka R and Hwang S. Development of a numerical model to predict heat exchange rates for a ground-source heat pump system. Energy and Buildings 40(12) (2008):2133–40

Nam Y, Ooka R. Numerical simulation of ground heat and water transfer for groundwater heat pump system based on real-scale experiment. Energy and Buildings 42(1) (2010):69–75

Pasquier P, Marcotte D. Short-term simulation of ground heat exchanger with an improved TRCM. Renewable Energy 46 (2012):92–9.

Pavković, B., Viličić, I.: A numerical and experimental investigation of the dynamic behavior of a heat pump. *Computational Engineering*, (2001), 679-690.

Rivera J.A., Blum P. and Bayer P. Analytical simulation of groundwater flow and land surface effects on thermal plumes of borehole heat exchangers. Applied Energy 146 (2015):421–33.

Ruiz-Calvo F, Rosa MD, Acuña J, Corberán JM, Montagud C. Experimental validation of a short-term Borehole-to-Ground (B2G) dynamic model. Applied Energy 140 (2015):210–23.

Tinti, F., Carri, A. Kasmaee, S., Valletta, A., Segalini, A., Bonduà, S. and Bortolotti, V. Ground temperature monitoring for a coaxial geothermal heat exchangers field: Practical aspects and main issues from the first year of measurements. Rudarsko Geolosko Naftni Zbornik 33(5) (2018):47-57

Webb, R.: Convective condensation of superheated vapor, *Transactions-american society of* *mechanical engineers journal of heat transfer*, 120 (1998), 418-421.

Zanetti, E., Azzolin, M., Bortolin, S., Busato, G., Del Col, D.: Design and testing of a microchannel heat exchanger working as condenser and evaporator, *17th International Refrigeration and Air Conditioning Conference at Purdue*, (2018).

Zakula, T., Gayeski, N., Armstrong, P, Norford, L.: Variable-speed heat pump model for a wide range of cooling conditions and loads, *HVAC&R Research*, (2011), 670-691.

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